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Knowledge infrastructures for the Anthropocene

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Abstract

The technosphere metabolizes not only energy and materials, but information and knowledge as well. This article first examines the history of knowledge about large-scale, long-term, anthropogenic environmental change. In the 19th and 20th centuries, major systems were built for monitoring both the environment and human activity of all kinds, for modeling geophysical processes such as climate change, and for preserving and refining scientific memory, i.e. data about the planetary past. Despite many failures, these knowledge infrastructures also helped achieve notable successes such as the Limited Test Ban Treaty of 1963, the ozone depletion accords of the 1980s, and the Paris Agreement on climate change of 2015. The article's second part proposes that knowledge infrastructures for the Anthropocene might not only monitor and model the technosphere's metabolism of energy, materials and information, but also integrate those techniques with new accounting practices aimed at sustainability. Scientific examples include remarkable recent work on long-term socio-ecological research, and the assessment reports of the Intergovernmental Panel on Climate Change. In terms of practical knowledge, one key to effective accounting may be 'recycling' of the vast amounts of 'waste' data created by virtually all online systems today. Examples include dramatic environmental efficiency gains by Ikea and United Parcel Service, through improved logistics, self-provision of renewable energy, and feedback from close monitoring of delivery trucks. Blending social 'data exhaust' with physical and environmental information, an environmentally focused logistics might trim away excess energy and materials in production, find new ways to re-use or recycle waste, and generate new ideas for eliminating toxic byproducts, greenhouse gas emissions and other metabolites.

Keywords

accounting, Anthropocene, climate change, infrastructure, knowledge infrastructures, technosphere

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The post-1950 Great Acceleration (Steffen et al., 2015) represents the aggregate effect of an expanding ‘technosphere’, conceptualized by Peter Haff (2014) as analogous to the biosphere or the lithosphere. Haff characterizes the technosphere as the global, ‘interlinked set of communication, transportation, bureaucratic and other systems’, *including human components*, that ‘act to metabolize fossil fuels and other energy resources’ (Haff, 2014). Like a huge super-organism, the technosphere seeks only to survive and grow. Through markets, the technosphere internalizes raw materials and energy supplies, but it externalizes waste as a valueless nuisance to be flushed into the global commons. The biosphere maintains a metabolic equilibrium, collecting virtually all of its energy from current (solar) inputs via photosynthesis and recycling nearly all of its wastes (Odum, 1991). In stark contrast, a large proportion of the technosphere’s energy supply comes from irreplaceable fossil sources, while much of its waste is toxic, inorganic, and/or long-lasting, generated in forms and quantities that overwhelm the biosphere’s capacity to absorb them.

The technosphere metabolizes not only energy and materials, but also information and knowledge. It ingests some as input and produces more as output. Global storage capacity in all forms – a reasonable proxy for information – grew from 2.6 billion gigabytes in 1986 to 295 billion gigabytes in 2007, a compound annual growth rate of 39% per year (Hilbert and López, 2011). From libraries to the Internet, huge information infrastructures organized and fueled that growth.

‘Information metabolism’ is no mere metaphor: if cloud computing were a country, it would be the world’s sixth largest consumer of electricity (Greenpeace International, 2014). This metabolism also generates waste, in the form of data that are never used. In recent years, however, ‘data exhaust’ – the information generated as a side effect of routine computational processes, such as records of search terms, web clicks and social media activity – has come to be seen as a resource that can be ‘mined’ by ‘big data’ analysis techniques to produce new insights (Brunk, 2001; Mayer-Schönberger and Cukier, 2013).

The widely circulated Great Acceleration graphs (Steffen et al., 2015) illustrate exponential post-1950 growth in dozens of socioeconomic and Earth System variables, from urban populations, water use and energy consumption to anthropogenic greenhouse gases, ocean acidification and nitrogen pollution from fertilizer runoff. The very existence of these graphs illustrates the rapid growth in another variable: human knowledge. Since 1925, the number of cited scientific publications (a mediocre, but useful proxy for scientific knowledge) has doubled every 8–10 years (Bornmann and Mutz, 2015). Especially since 1950, many governments and large corporations have institutionalized and routinized scientific research and technological development. One need not deny the sophistication of previous eras’ understanding (Bonneuil and Fressoz, 2016) or adopt a triumphalist Enlightenment optimism to accept that, compared with 1950, we know much more today. We have much more data and much better understanding not only of the natural world, but also of human economies, populations, wastes and nearly everything else.

Both the technosphere and the Anthropocene itself are colossal abstractions, obscuring messy details and contradictions as well as differential costs, benefits and responsibilities (Haraway, 2015). Yet as unifying frameworks for grasping extremely complex interactions, they can also bring clarity and coherence. Leaving critique to others, this article focuses on what I will call ‘Anthropocene knowledge’ about large-scale, long-term, anthropogenic environmental change. Building on extensive historical research, the article asks: Where did Anthropocene knowledge come from? What kinds of knowledge infrastructures might help to account for *and ultimately to refashion* the techno-metabolic processes currently pushing Earth systems past the limits of a ‘safe operating space for humanity’ (Rockström et al., 2009)? How could recycling ‘data exhaust’ help to reduce consumption, waste and environmental damage?

Monitoring, modeling, memory: A brief history of Anthropocene knowledge

Virtually everything we know about the Anthropocene as a geophysical, ecological, and social phenomenon comes to us from scientific knowledge infrastructures built in the 20th century.

Knowledge infrastructures are 'robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds' (Edwards, 2010). Examples of well-functioning knowledge infrastructures include national censuses, weather forecasting and the Centers for Disease Control. Like physical infrastructures, such as container transport or cellular telephony, they display qualities of modularity, scaling and networked organization. They are composed of many interacting, yet largely independent groups and institutions, each with its own imperatives, values, resources, revenue streams and temporal orientations (Borgman et al., 2014; Edwards et al., 2013; Ellen et al., 2011). My usage here stresses the 'routine, reliable, and widely shared' aspects of infrastructure. I take a pragmatic view of 'knowledge' as *useful understanding* of patterns and causal relationships, expressed in a *shared vocabulary* (including math and statistics), and backed by *data* (evidence).

Many scientific knowledge infrastructures share a common set of functions.[1] They *monitor* features of interest, *model* complex systems to find and test causal relationships, and record data in *memory* systems to track change over time. Data from systematic monitoring grounds our awareness of global environmental and social change. For example, weather records dating to the mid-19th century support today's knowledge of climate change (Edwards, 2010). Beginning with the 1957–1958 International Geophysical Year (IGY), and spurred by Cold War geopolitics, many sciences sought planetary-scale knowledge by constructing permanent global monitoring networks on land, in the air, at sea and in outer space – a pattern I have called 'infrastructural globalism' (Edwards, 2006). In the 1970s, as awareness of environmental problems mounted, these networks grew in scope and importance, often loosely organized at the international level by such agencies as the UN Environment Programme and the International Council of Scientific Unions (ICSU). Across the same time period, social systems around the world were also increasingly 'instrumented' with 'sensors' of many kinds, such as opinion polls and obligatory reporting of demographic, economic, health, agricultural and other social data to national governments and the United Nations (Burke, 2012).

Modeling has played an equally important role in generating Anthropocene knowledge. Simulation models can test theoretical understanding of complex, interactive processes – especially those for which experimental methods are infeasible, such as global climate or tectonic plates. Combined with empirical data, modeling can explain the past and help project the future consequences of both human and natural changes, such as ozone depletion or climate change (Edwards, 2016b). Modeling can create cross-talk among scientific disciplines. For example, in the 1970s, the rise of climate change as a research concern prompted the first meetings on environmental biogeochemistry, and ecologists began to model the carbon cycle. In the social sciences, behavioral economics combined experimental methods with insights from cognitive and social psychology to revise simplistic 'rational actor' models (Akerlof and Kranton, 2010; Kahneman, 2011).

The Anthropocene concept is inherently temporal and comparative (Zalasiewicz et al., 2015). So Anthropocene knowledge depends crucially on long-term *memory*. Data collected by previous generations, using instruments, standards and techniques that have evolved continually over many decades, must be aligned with data taken more recently to create a coherent long-term record. Therefore, scientific memory requires metadata, such as information about where, when, and how measurements were taken. Metadata are often incomplete or otherwise imperfect; to the extent that additional metadata can be recovered, data images of the past are subject to ongoing change (Edwards et al., 2011).

By the 1960s, infrastructural globalism had become a prominent feature of many Earth sciences. IGY ideas had begun to establish common ground among them through its 'single physical system hypothesis', harbinger of today's 'Earth System science'. The pattern of infrastructural globalism is clearest with respect to environmental and social *monitoring* and *memory*. International networks *made global data* through collection, standardization and sharing. With these systems in place, scientists proceeded to *make data global*, creating rich, long-term global data images from heterogeneous sources through careful comparison and adjustment (Edwards, 2010). Less obviously, *modeling* of Anthropocene concerns also played a role in infrastructural globalism. Knowledge integration efforts such as the Coupled Model Intercomparison Project (Taylor et al., 2011), the Earth System Modeling Framework (Valcke et al., 2016) and the Intergovernmental Panel on Climate Change assessments (IPCC, 2013) transformed modeling from a craft enterprise to a widely accepted, if still controversial, element of knowledge infrastructure in the Earth System sciences.

Paradigms for Anthropocene knowledge infrastructures

What kinds of knowledge infrastructures might help to mitigate the technosphere's environmentally destructive disequilibrium?

In a few important cases, humanity has successfully applied knowledge gained from the approaches described above to reduce or even reverse environmental damage. For example, in the 1950s, worldwide monitoring of fallout from atmospheric tests of nuclear weapons demonstrated the global spread of dangerous radionuclides, raising alarm about potential consequences for both human health and natural ecosystems. These concerns led to the 1963 Limited Test Ban Treaty prohibiting all but underground nuclear tests. The ban would not have been politically possible in the absence of seismic and atmospheric monitoring networks that permitted the remote detection of weapons tests without intrusive inspections. Meanwhile, scientific monitoring of fallout and bomb-generated radiocarbon (C_{14}) provided unexpected data and insights into atmospheric circulation and the carbon cycle (Edwards, 2012). As a second example, the science of chlorofluorocarbon chemistry raised the alarm over anthropogenic ozone depletion. When the global ozone monitoring network detected the Antarctic 'ozone hole', political action swiftly followed: the Vienna Convention (1985) and the Montreal Protocol (1987), which banned many ozone-depleting chemicals. As a direct result, the ozone layer has stabilized since about 2005, and is expected to recover entirely in the next few decades. A final example might be the 2015 Paris Agreement on climate change. Weaker than many had hoped, the Paris Agreement still represents a major step toward decarbonizing the global economy and avoiding the worst scenarios of anthropogenic climate change.

One model for Anthropocene knowledge infrastructures might thus be the IPCC, whose assessments form the knowledge base for negotiations under the UN Framework Convention on Climate Change (UNFCCC). Honed over almost 30 years through five iterations (1990, 1995, 2001, 2007 and 2013), the IPCC knowledge assessment process is doubtless the most inclusive one ever devised. Its designers sought to reduce lags in social and institutional learning by bringing stakeholders into knowledge production directly, through an extensive peer review process. IPCC protocols invite not only scientists, but also governments and non-governmental organizations, to comment in detail on any aspect of draft IPCC reports. IPCC authors are then required to respond to *all* of the many thousands of comments they receive. The IPCC process helped create global, interdisciplinary scientific communities oriented to a common problem, and it established benchmarking techniques that brought a degree of standardization to climate modeling and data analysis (Taylor et al., 2011). Finally, it resulted in a remarkable data sharing infrastructure, the Earth System Grid Federation (Williams et al., 2013).

On the downside, the time-intensive IPCC process became a heavy burden for many research scientists, resulting in fatigue, career stalls, leadership turnover and problems recruiting co-authors for the reports' many long chapters. The long, difficult history of global climate negotiations – initiated nearly 30 years ago – reinforces the well-known lessons that knowledge alone cannot dictate policy choices, and that politically controversial knowledge often generates confusing (if sometimes valuable) counter-expertise as well as motivated reasoning[2] on the part of those who stand to lose something. Finally, as many critics have observed, knowledge about the global scale can prove very difficult to translate into actionable knowledge at national or local scales (Beck et al., 2014; Hulme, 2009, 2010). As a result, *downscaling* knowledge has become a central focus of the climate research community (Edwards, 2016a). Examples include climate change projections at the scale of counties and city regions (already in use by city planners, public health agencies, and watershed and port managers) and statistical assessments of how much climate change contributes to individual extreme weather events (National Academy of Sciences, 2016).

The IPCC assessment approach is the apotheosis of 20th-century infrastructural globalism: the deliberate construction of world-scale, quasi-centralized observing and analysis systems. In the 21st century, new approaches to Anthropocene knowledge might come from other, much more distributed modes of production. The analogy to waste recycling in ecosystems, discussed above, suggests one such approach: could the technosphere learn to recycle waste information?

Among the great discoveries of the late 20th century was that virtually all information processes not only use data, but also *generate* data about users and uses, often as a byproduct (Brunk, 2001; Zuboff, 1988). Today, 'data exhaust' is produced by most online activity, from web searches and downloads to social media posts and shopping. Analogous to the biosphere's reuse of organic wastes, numerous online systems – Google's search algorithms, recommender systems from Netflix and Amazon, etc. – recycle these byproducts of intelligent human activity to create more intelligent artificial behavior.

The 'mining' of data exhaust to detect patterns, trends and individual preferences is transforming the relationship between designers, builders, marketers and consumers, as well as civil society, worldwide. It is also transforming science. In 2014, the Centers for Disease Control awarded a US$75,000 prize for improved prediction of influenza dynamics. The winning scientists deployed a data assimilation system explicitly based on weather forecasting techniques. They combined a CDC simulation model of disease spread with real-time Google data from flu-related searches, producing the most accurate real-time forecast of the 2012–2013 flu season (Shaman et al., 2013). Other researchers have used mobile phone location and movement to study the interplay between changing weather and aggregate social behavior in cities, and in many other ways as well (Sagl et al., 2012). Apps such as Google Maps, making use of smartphones' GPS sensors to track their owners' movement, already help to optimize urban traffic flows by warning drivers of slowdowns and providing alternate routes.

These and similar innovative techniques have been described as an emerging 'fourth paradigm' of data-intensive science. (The other three are theory, experiment and simulation.) Following the pattern of infrastructural globalism, massive, high-resolution sensor networks provide more, finer-grained environmental information (Hey et al., 2009). Under more recent approaches, scientists seek patterns opportunistically in large data sets created for other reasons; conduct meta-analyses of existing studies; and open up the vast existing stores of 'dark data' available from past research

(Hampton et al., 2013). In the long run, these approaches promise new ways to monitor, analyze and potentially to optimize the technosphere's environmental impacts. However, the data utopia envisioned by some faces a host of difficult, sometimes irresolvable issues, including data friction, data ownership, personal privacy, and metadata quality (Edwards et al., 2011).

Still other, very different models for Anthropocene knowledge infrastructures might be the practical sciences of accounting and logistics. Nearly opposite to the top-down, globalist approach symbolized by the IPCC, these sciences operate on the scale of firms and other organizations.

Accounting simply means knowing what one takes in, what one spends, and how one's assets move and change. Whether assets are conceived as money, people, equipment or carbon, accurate accounting is the first step to optimizing processes. Recently, a remarkable program of long-term socio-ecological research (LTSER) has developed material and energy flow accounting (MEFA) methods to track energy, raw materials, and wastes over many decades, at scales ranging from individual cities to bioregions. Making use of many kinds of data, comparative analysis of farming practices in Austria and Kansas between 1880 and 1940 (for example) revealed that

> whereas Old World farms had abundant human and animal labour but a shortage of land, Great Plains farms had excess land and a shortage of labour and livestock … Old World communities kept more animals than needed for food and labour to supply manure that maintained cropland fertility. Great Plains farmers used few animals to exploit rich grassland soils, returning less than half of the nitrogen they extracted each year. Relying on a stockpiled endowment of nitrogen, they produced stupendous surpluses for market export, but watched crop yields decline between 1880 and 1940 … Kansas farmers faced a soil nutrient crisis by the 1940s, one that they solved in the second half of the twentieth century by importing fossil fuels. Austrian and Great Plains agriculture converged thereafter, with dramatically increased productivity based on oil, diesel fuel, petroleum-based pesticides and synthetic nitrogen fertilisers manufactured from natural gas. (Singh et al., 2013: 269–270)

Complementing this crucial long-term perspective, environmentally aware accounting can optimize sociotechnical processes through such methods as life cycle assessment, encompassing all aspects of a production chain from raw materials to energy to waste (Lifset, 2012). Through modeling and standardized approaches, such assessments permit rigorous comparison of (for example) the carbon footprints of different energy production processes. Similar life-cycle approaches are being applied in the design of closed-loop, zero-waste manufacturing processes and supply chains (Winkler, 2011). The ultimate goal – mimicking the biosphere's near-complete recycling of waste – will likely never be achieved, but these techniques may offer an approximation in some domains.

Emerging practices of 'carbon accounting' attempt to bring greenhouse gas emissions from fossil fuels into the economy by pricing them, whether through taxes on consumption, cap-and-trade systems, or wellhead fees. Other examples of an accounting-oriented approach are climate risk valuation tools. These systems, as envisioned by the Task Force on Climate-related Financial Disclosures (Elliott, 2015), would generate standardized measures of corporations' exposure to risks from climate change, such as 'stranded assets' (e.g. coal and oil reserves that cannot be mined, or beach resort hotels threatened by rising sea levels). Such tools could encourage financial markets to internalize climate change concerns via the pricing of stocks and bonds.

Even without carbon pricing, the 'carbon footprint' increasingly serves as a common framework for assessing the environmental impact of virtually any human activity or product. Carbon accounting creates a kind of common currency, connecting fossil fuel consumption to forest destruction, cattle belches, and refrigerants. The notion of 'embodied carbon' – the greenhouse gases generated in manufacturing and transporting a product – alters the picture of responsibility for emissions: declines in US and European carbon emissions result in part from the rise of global trade, while rising Chinese emissions stem largely from its manufacture of products that are consumed elsewhere. Currently, most carbon metrics are flawed, gameable and fragile, as well as overly reductive, covering only a few elements of environmental concern (Ascui, 2014; Mol, 2012; Whitington, 2016). Yet in the future, routine and standardized carbon accounting, in concert with other accounting practices, might provide important knowledge relevant to reducing human damage to Earth systems. At a minimum, such accounting will be needed to monitor the Paris climate treaty.

The science of logistics focuses on supply chains, especially transport, coordination and storage. Since the 1960s, multinational corporations have transformed their operations through increasingly powerful information systems, developing precise and timely methods of tracking, moving, assembling and delivering goods, services and finance across intricate global supply chains (Castells, 2000; Cowen, 2014). More efficient use of materials and energy in the service of sustainability can complement the primary corporate goal of cost reduction. For example, in 2015 the Ikea Corporation got 53.4% of the energy its operations consume from the company’s own wind, solar, and biomass installations, with a goal of 100% by 2020. The company maximizes direct delivery from suppliers to stores, rather than to a warehouse, decreasing travel time and energy consumption (Ikea Corporation, 2016). In a second example, United Parcel Service (UPS) equipped some of its 100,000 delivery vehicles with ‘telematics’ sensors monitoring speed, braking, engine performance, stop time and engine performance. The telematics program also deployed sensor data as feedback to drivers, retraining them to accelerate more slowly, brake more smoothly, and reduce idling time (United Parcel Service, 2014). Combining telematics data with computer-optimized routing, UPS cut fuel use by a dramatic 50% between 2004 and 2012.

Optimistic examples such as those just offered are obviously offset by many contrary phenomena: the Jevons paradox or rebound effect, by which energy saved in one process is viewed as a bonus and immediately re-consumed elsewhere; the large and growing energy costs of computing itself; economic competition, in which successful but costly improvements in sustainability are constantly undercut by less expensive, more wasteful alternatives; and the adverse social consequences of some modes of optimization, such as increased surveillance, oppressive work discipline, and the disintegration of organized labor. The technosphere, as Haff pictures it, responds mainly to its own, internal, environmentally destructive logic, for which some have put forward terms such as ‘Capitalocene’ or ‘Plantationocene’ (Haraway, 2015; Moore, 2014). Today’s consumerist, hugely unequal societies certainly drive overheated growth – but achieving a minimally acceptable standard of living for 9 billion people by 2050 will not be possible under *any* imaginable economic system without massive environmental stress. Perhaps the technosphere’s human components can no longer transform this logic, so profoundly has it been literally built into the world we now inhabit, with its enormous incentives to continue in a business-as-usual mode. It may at best be possible to steer it, and conceivably to buy some time. Nevertheless, even knowing this, we must make the effort.

Conclusion

Systems thinking is fundamentally hard for human beings, because of complexity and counterintuitive feedbacks (Sterman, 2008). The power of the Anthropocene epoch and the technosphere, as conceptual tools, lies in their insistence on a large-scale, long-term, systemic grasp of phenomena too often siloed into separate disciplines or analyzed as local or short-term concerns. Viewed as the products of historical knowledge infrastructures, these concepts also draw attention to a post-1950 ‘great acceleration’ in scientific understanding, driven in large part by rapid advances in information processing, from sensors and data collection to computer simulation and networked resources.

As a result, a vast array of systems data is no longer difficult to come by, while tools for systems modeling are widely available. Meanwhile, a ‘fourth paradigm’ of data-intensive science is adding new dimensions to monitoring, modeling and memory. Together, these methods offer at least the possibility of knowledge infrastructures better able to understand, and perhaps to better manage, the challenges of the Anthropocene and the failures of the technosphere.

Here I have argued that the globalist knowledge infrastructures of the 20th century will be complemented and extended through 21st-century data-intensive science. Where the former were often constructed in a top-down, purposeful and aggregative manner, the latter may be built bottom-up and opportunistically, driven by practice rather than design. Both will play key roles in building knowledge that is useful and useable for the Anthropocene. Blending social ‘data exhaust’ with physical and environmental information, environmentally focused accounting and logistics might trim away excess energy and materials in production, find new ways to re-use or recycle wastes, and reduce toxic byproducts, greenhouse gas emissions, and other noxious metabolites. Will these knowledge infrastructures succeed? Can we afford for them to fail?

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Notes

1. Many other legitimate, important modes of knowing the world exist, and sometimes conflict with scientific understanding (Hulme, 2009). In my view, only the scientific mode has been capable of environmental analysis at the global scale.
2. In psychology, ‘motivated reasoning’ refers to individuals’ tendency to defend their existing beliefs against disconfirming evidence, using various apparently rational strategies.

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